

# Understanding Predictability of the Ocean

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## LONG-TERM GOALS

The long-term scientific goals of this research project are:

1. To develop an understanding of how some observations affect ocean predictability.
2. To further develop the state-of-the-art ROMS 4D-Var by extending the observational types and applications.
3. To gain experience and develop ideas for the limitations to the predictability of oceanic processes.
4. To train a new generation of students in data assimilation and ROMS.
5. As a YIP award, to strengthen the early career and build the research path for myself as young faculty.

## OBJECTIVES

The primary objectives of this project are: (i) explore the capabilities of a real-time ocean state-estimation and prediction system; (ii) to assess how particular observations may affect predictability; (iii) to compare these results with full ocean-state estimates generated from the ΨEX acoustic experiment; and, (iv) provide means to build a research program for early career scientist.

## APPROACH

In this YIP award, my aim is to characterize the factors that control predictability in the ocean, particularly around Hawaii and the North Philippine Sea (which resides within the internal wave train from the Luzon Strait as well as interacting internal waves generated at the Mariana islands). To accomplish this goal requires a number of studies into understanding the role of internal tides interacting with mesoscale energy, quantifying the role of observations in sampling such difficult dynamical regimes, extending the capability of the assimilation procedure to utilize advanced observational datasets (high-frequency radar and acoustic tomography), develop further improvements to the state-estimation procedure, and to help quantify the role of errors in models. Furthermore, as a YIP award, the goal is to build a successful academic research program under

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my direction. Because of the large scope of these issues, the work carried under this YIP award both leverages and contributes to work in other funded projects.

As part of the NOAA-funded Integrated Ocean Observing System (IOOS) effort, I lead the ocean modeling effort of the Pacific IOOS (PacIOOS) region. The ocean model used in this research is the ONR-funded Regional Ocean Modeling System (ROMS): a free-surface, hydrostatic, primitive equation ocean model discretized with a terrain following vertical coordinate system. ROMS has been successfully used to model many regions of the world ocean (see <http://www.myroms.org/papers>) and is a widely used community resource.

The oceanic modeling component of PacIOOS currently employs four nested ROMS models of Hawaii: 4km island-chain, 1km Oahu, 100m Oahu South-Shore, and 80m Oahu West-Coast. Each grid is nested in the grid above it (both the South and West models are nested in the Oahu grid), and the 4km is nested in the real-time NCOM. This system is currently running operationally, and it assimilates the previous four days of real-time observations into the 4 and 1 km models using 4D-Var to produce nowcast state-estimates. From the nowcasts, a seven day prediction is made, which is used by the local community (e.g., Coast Guard search and rescue, Shipping Routes, etc.). In addition, we now operate assimilation and prediction models for the Philippine Sea, Mariana Islands, Guam, and American Samoa. These efforts are both leveraged and extended from the work in this YIP. The system currently does not employ tides, and this is a significant shortcoming, as described above.

In addition, we have developed a model of the Philippine Sea for conducting corollary research in a region with significant energies at all oceanic length-scales from planetary (with the formation of the Kuroshio current) down to sub-mesoscale and strong internal tides. In collaboration with ONR Acoustics, we have worked on the  $\Psi$ Ex program to study the Philippine Sea and develop a technique for assimilation of acoustic travel time data from the experiment. The Philippine Sea is characterized by strong tidally induced internal waves, and internal tides are known to influence acoustic propagation. What is not well known is the combined effect that these varying energetic dynamical scales (internal tides, sub-mesoscale and mesoscale, and low-frequency dynamics) have upon the travel-times of acoustic rays in the Philippine Sea.

To improve forecasts of the ocean circulation, we must understand how both observations and model error (such as the incorrect tidal phasing) impact the predictability. Forecasts are limited by the growth of uncertainty, and the aim is to quantify the uncertainty in forecasting regional oceans to the observations and configuration. To expand our operational capabilities, we have developed and implemented assimilation techniques for HF radar and acoustic travel-times. To understand the importance of observations, we have implemented an adjoint of the observation-space assimilation procedure for the Hawaiian regional model to quantify the sensitivity of the forecast to satellite, autonomous gliders, and long-term fixed mooring data.

As part of the Young Investigator Program, development of a dynamic research group is one of the primary objectives. In the reporting year, in my group there were: three post-doctoral researchers, and two graduate students (1 M.S. level and 1 Ph.D.). One M.S. student graduated in the spring, and two post-docs have received permanent positions elsewhere.

## WORK COMPLETED

The focus of the work for this reporting period is on the Philippine Sea, a region of strong ocean variability and of significant national interest to the Navy.

During the current reporting period, we have completed the following tasks:

- i) I have published a manuscript (Powell et al., 2013) that uses the adjoint model to examine how the Philippine Sea affects the time variability of the acoustic travel-time. This work is important because if the sensitivity to the ocean is significant (more than 200 msecs) and varying, it requires that our ocean estimate be consistent before we can attempt to assimilate the data. As part of this work, I have been invited to present the results at the ASA meeting in Dec.
- ii) We have published a paper (Kerry et al., 2012) that shows the important effects of remotely-generated internal tides on estimates of local tidal conversion in the Philippine Sea. In many regions of the world's oceans, remote internal tides (predominately Mode-1) propagate into the region and can significantly impact local tidal conversion. For regional modeling of regions with strong tides, this has significant effect on how the regional model is configured. She is now working to understand the interaction between the internal tides and the mesoscale on our ability to predict the mesoscale and represent observations that include all scales.
- iii) We currently have two papers in revision to *J. Phys. Oceanogr.* that examine the interaction of internal tides with the mesoscale in the Philippine Sea. The mesoscale has a significant impact on the generation and propagation of internal tides throughout the ocean through changes to the waveguide as well as increased turbulent mixing of the wave. These results have important consequences for identifying the importance of tidal physics on the predictability of the region.
- iv) I have developed a twin experiment to explore the assimilation of acoustic travel-time data. The preliminary results are very encouraging using fixed ray-paths, and it is hoped to expand this to variable ray-paths in the future. The twin experiment covers the region of the  $\Psi$ Ex in the Philippine Sea.
- v) I have published a book chapter (Powell, 2013) examining how to avoid overfitting of observations using additional outer-loops in data-space 4D-Var methods. The paper examines the proper constraint and how ignoring the constraint improves the fit to the observations, but reduces the predictive skill of the model.
- vi) I have developed an operational model of the Philippine Sea (see Figure 1) and Guam (see inset rectangle of Figure 1) that, each day, assimilate the previous three days worth of data and generate a one week forecast. In addition, we are working to bring a similar system for American Samoa online.
- vii) Most significantly, the lessons of these assimilation experiments and observational impacts **are now in operational use** with the PacIOOS ocean estimation and prediction system. Results can be found at <http://pacioos.org/roms>
- viii) One Ph.D. student fully funded by this project has passed both her qualifying and comprehensive exams in the past year, and she is scheduled to defend her thesis this year (the final reporting year of this project).
- ix) A total of 12 manuscripts have been published in top peer-reviewed journals in oceanography along with 2 Masters Theses have been fully or partially supported by this award.
- x) Mentored four post-doctoral researchers, four graduate students, and one technician.

## RESULTS

A brief summary of some of the most interesting points from the work completed is described below.

The Philippine Sea is an important part of the North Pacific sub-tropical gyre as the formation region of the Kuroshio western boundary current. The region is traversed by a band of enhanced eddy kinetic energy centered at 22°N resulting from baroclinic instability associated with the vertical shear between the two dominant jets of the area. The region is characterized by very strong barotropic to baroclinic tidal conversion that interacts with this strong mesoscale field. It is a region that is very difficult to predict with significant skill. We have examined how these tides interact with the mesoscale, and the results provide greater insight into these important ocean dynamics.

Barotropic to baroclinic conversion at the Luzon Strait is affected by local changes in stratification over the generation site and the varying influence of remotely generated internal tides from the Mariana Arc. When the internal tide generation at the Mariana Arc was also varying due to the effects of the mesoscale circulation, the variability at the Luzon Strait was 76% higher than the case without remotely generated internal tides. The changes in generation energy levels result from the combination of changing stratification over the Luzon Strait generation site, variability in the propagation of fluxes from the Mariana Arc, and varying generation at the Mariana Arc. As shown in Figure 2, the flux of internal tide energy is significantly altered by the changes in stratification due to the location of the Kuroshio Loop Current.

This study shows that both the temporally and spatially varying general ocean circulation and the background internal tide field influence model estimates of baroclinic tides in the Philippine Sea. The results provide insight into the mechanisms of variability of the baroclinic tides and highlight the importance of considering both the remotely generated internal tides and the sub-tidal dynamics to estimate internal tide energetics. Understanding the spatial and temporal variability of the internal tides is important when interpreting observations of internal tide energetics and ocean mixing and developing parameterizations for climate-scale models.

These results have a significant impact on how we deal with a variety of observations in the operational Philippine Sea system as well as with the acoustic travel-time assimilation experiments.

## IMPACT/APPLICATIONS

With our work on the interaction of internal tides with the mesoscale and the impact upon predictability of the Philippine Sea, we are at the forefront of numerical modeling and oceanic mixing processes and combining these representations with observations with modified assimilation procedures. The role that the mesoscale plays in conversion will be very significant as our work has shown that the phasing of the remote internal tides is dramatically altered by the changing stratification due to mesoscale activity. This alters the flux beams and propagation speeds and greatly diminishes our predictive skill.

We are operating one of very few operational oceanic 4D-Var estimation and ensemble prediction systems, and we are operating two: Hawaii and Philippine Sea. We are also the only one that generates daily observational impact analyses that we use to monitor the observations and understand how best to improve our estimate and forecasts.

As numerical models are becoming more widely accepted in oceanographic applications, a quantified estimate of the uncertainties must accompany any forecast to aid in the understanding

of the generated fields. This project will contribute to the ROMS community by deploying methods to quantify how observations contribute to prediction. The foundation for this work is present only in ROMS as it is the only model that possesses such a wide range of 4D-Var algorithms. This project will contribute to further enhancement and development of these tools and algorithms.

## TRANSITIONS

In addition to the published papers, the cutting edge work of the observational impact was presented at invited lectures in the past year. Dr. Powell presented an invited talk at the International ROMS/TOMS Workshop in 2012. A post-doc in my lab, Joao Souza, presented another paper at the same meeting. In addition, my Ph.D. graduate student, Colette Kerry, presented her work at CSIRO in Australia.

We are also working with projects that collaborate with NRL-Stennis to facilitate open communication.

## RELATED PROJECTS

This project is collaborating with the following ONR supported projects:

- “A community Terrain-Following Ocean Model (ROMS)”, PI Hernan Arango, grant number N00014-08-1-0542.
- “North Pacific Acoustic Laboratory: Deep Water Acoustic Propagation in the Philippine Sea,” PI Peter Worcester, ONR Grant N00014-08-1-0840.

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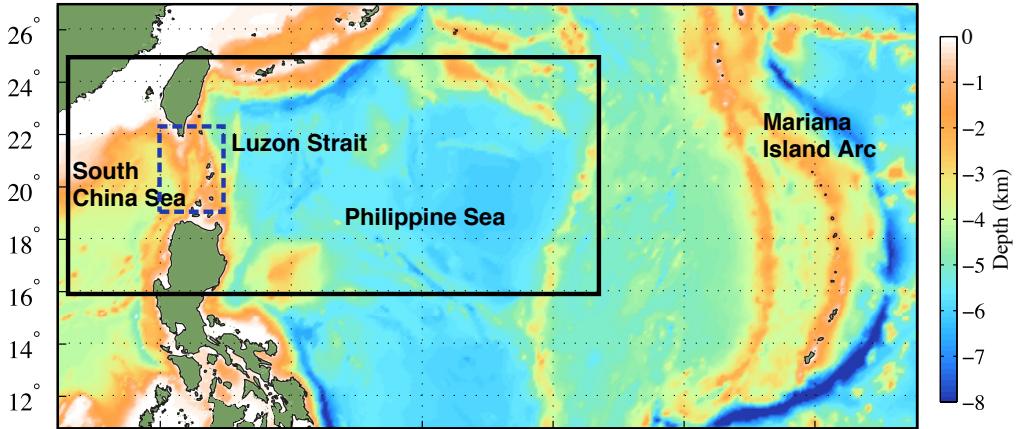


Figure 1: Model domain for operational Philippine Sea at 8km resolution. The small, inset box shows the Guam domain, while the large box show the twin experiment domain for the acoustic travel-time assimilation experiments.

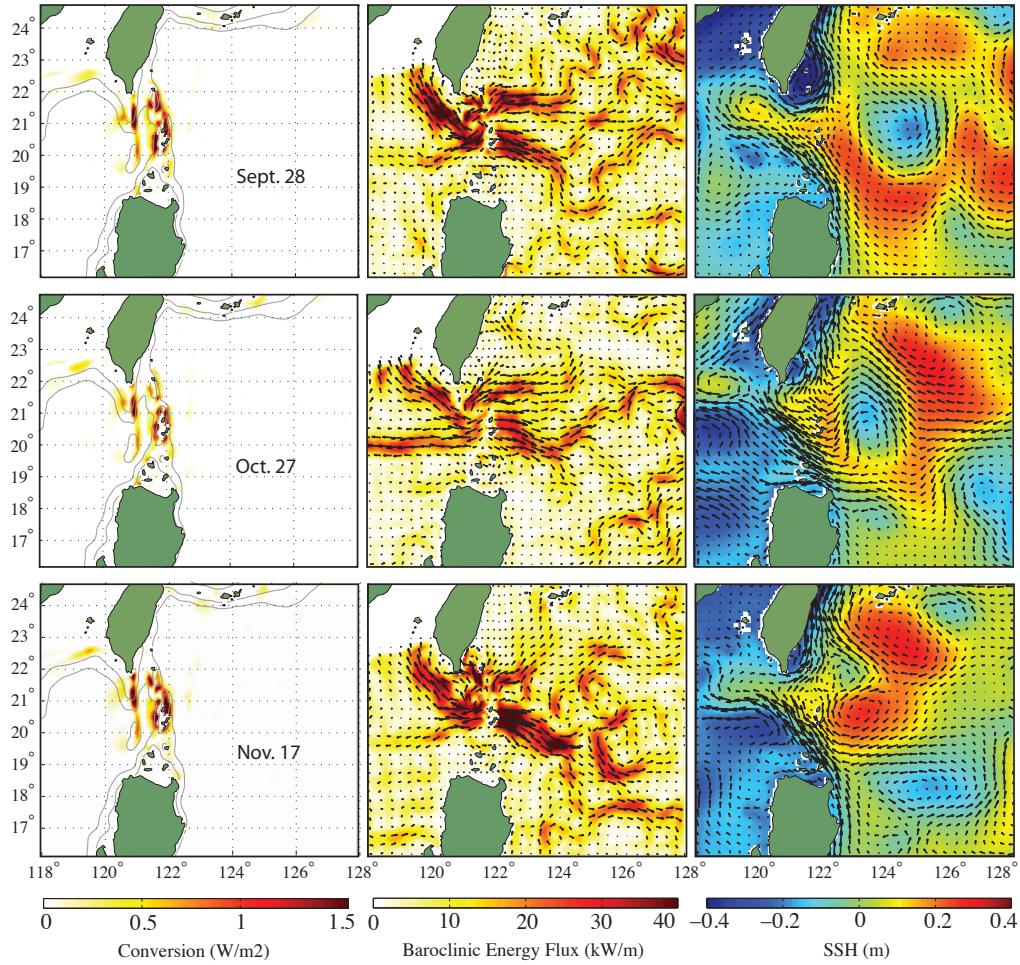


Figure 2:  $M_2$  barotropic to baroclinic conversion averaged over 5 tidal cycles up to Sept. 28, Oct. 27 and Nov. 17 2010, with 1000 and 2000 m depth contours shown in grey.  $M_2$  depth-integrated baroclinic energy fluxes, and detided SSH anomaly and surface current velocity vectors.